References and Notes
1. M. A. El-Sayed, *Acc. Chem. Res.* **34**, 257 (2001).
2. C. B. Murray, C. R. Kagan, M. G. Bawendi, *Annu. Rev. Mater. Sci.* **30**, 545 (2000).
3. V. C. Sundar, H. J. Eisler, M. G. Bawendi, *Adv. Mater.* **14**, 739 (2002).
4. M. A. Petruska, A. V. Malko, P. M. Voyles, V. I. Klimov, *Adv. Mater.* **15**, 610 (2003).
5. C. T. Black, C. B. Murray, R. L. Sandstrom, S. H. Sun, *Science* **290**, 1131 (2000).
6. M. Pileni, *J. Phys. Chem. B* **105**, 3358 (2001).
7. A. A. Middleton, N. S. Winggreen, *Phys. Rev. Lett.* **71**, 3198 (1993).
8. R. Parthasarathy, C. M. Lin, K. Elteto, T. F. Rosenbaum, H. M. Jaeger, *Phys. Rev. Lett.* **92**, 076801 (2004).
9. M. Bruchez, M. Moronne, P. Gin, S. Weiss, A. P. Alivisatos, *Science* **281**, 2013 (1998).
10. Details of the synthesis and characterizations are available on *Science* Online.
11. J. Beck *et al.*, *J. Am. Chem. Soc.* **114**, 10834 (1992).
12. C. B. Murray, C. R. Kagan, M. G. Bawendi, *Science* **270**, 1335 (1995).
13. A. P. Alivisatos *et al.*, *Nature* **382**, 609 (1996).
14. C. A. Mirkin, R. L. Letsinger, R. C. Mucic, J. J. Storhoff, *Nature* **382**, 607 (1996).
15. M. Brust, M. Walker, D. Bethell, D. J. Schiffrin, R. Whyman, *J. Chem. Soc. Chem. Commun.* **1994**, 801 (1994).
16. Y. Lu *et al.*, *Nature* **389**, 364 (1997).
17. D. A. Doshi *et al.*, *Science* **290**, 107 (2000).
18. C. P. Collier, R. J. Saykally, J. J. Shiang, S. E. Henrichs, J. R. Heath, *Science* **277**, 1978 (1997).
19. H. Grabert, M. H. Devoret, *Single Charge Tunneling* (Plenum, New York, 1992).
20. C. A. Neugebauer, M. B. Webb, *J. Appl. Phys.* **33**, 74 (1961).
21. D. L. Peng, K. Sumiyama, S. Yamamuro, T. Hihara, T. J. Konno, *Appl. Phys. Lett.* **74**, 76 (1999).
22. A. J. Rimberg, T. R. Ho, J. Clarke, *Phys. Rev. Lett.* **74**, 4714 (1995).
23. Y. F. Lu *et al.*, *J. Am. Chem. Soc.* **122**, 5258 (2000).
24. C. A. Stafford, S. Das Sarma, *Phys. Rev. Lett.* **72**, 3590 (1994).
25. G. Kirczenow, *Phys. Rev. B Condens. Matter* **46**, 1439 (1992).
26. V. I. Klimov *et al.*, *Science* **290**, 314 (2000).
27. B. Dubertret *et al.*, *Science* **298**, 1759 (2002).
28. W. H. Press, B. P. Flannery, S. A. Teakolsky, W. T. Vetenling, *Numerical Recipes* (Cambridge Univ. Press, Cambridge, UK, 1986), chap. 14.

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Probabilistic Integrated Assessment of "Dangerous" Climate Change

Michael D. Mastrandrea[1]* and Stephen H. Schneider[2]

Climate policy decisions are being made despite layers of uncertainty. Such decisions directly influence the potential for "dangerous anthropogenic interference with the climate system." We mapped a metric for this concept, based on Intergovernmental Panel on Climate Change assessment of climate impacts, onto probability distributions of future climate change produced from uncertainty in key parameters of the coupled social-natural system—climate sensitivity, climate damages, and discount rate. Analyses with a simple integrated assessment model found that, under midrange assumptions, endogenously calculated, optimal climate policy controls can reduce the probability of dangerous anthropogenic interference from ~45% under minimal controls to near zero.

Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) states its ultimate objective as "Stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (*1*). This level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner. Thus, the criteria for identifying "dangerous anthropogenic interference" (DAI) may be characterized in terms of the consequences (or impacts) of climate change (*2*). Although these impacts, and a precise definition of DAI, are subject to considerable uncertainty, a plausible uncertainty range can be quantified from current scientific knowledge (*3*). We argue that climate change policy decisions should be conceptualized in terms of preventing or reducing the probability of DAI, a risk-management framework familiar to policymakers and an outcome to which more than 190 signatories to the UNFCCC have committed.

Research related to global climate change must deal explicitly with uncertainty about future climate impacts. Due to the complexity of the climate change issue and its relevance to international policymaking, careful consideration and presentation of uncertainty is important when communicating scientific results (*2*, *4–7*). Policy analysis regarding climate change necessarily requires decision-making under uncertainty (*8–10*). Without explicit efforts to quantify the likelihood of future events, users of scientific results (including policy-makers) will undoubtedly make their own assumptions about the probability of different outcomes, possibly in ways that the original authors did not intend (*11*, *12*).

Assigning likelihoods to potential future worlds is difficult, as noted by Grübler and Nakicenovic (*13*), because any such estimates will be highly subjective and based on assessments of future societal behavior and values. Uncertainty, they warn, may alternatively be dismissed or replaced by spurious expert opinion. Although the suitability and effectiveness of techniques for presenting uncertain results is context-dependent, we believe that such probabilistic methods are more valuable for communicating an accurate view of current scientific knowledge to those seeking information for decision-making than assessments that do not attempt to present results in probabilistic frameworks (*14*).

We present a metric for assessing DAI: a cumulative density function (CDF) of the threshold for dangerous climate change. We demonstrate its utility by applying it to modeled uncertainty in future climate change using an optimizing integrated assessment model (IAM). IAMs are common policy analysis tools that couple submodels of the climate and economic systems, balance costs and benefits of climate change mitigation to determine an "optimal" policy (*15*), and often exhibit properties not apparent in either submodel alone (*16*).

We chose Nordhaus' Dynamic Integrated Climate and Economy (DICE) model (*17*) for our analysis because of its relative simplicity and transparency, despite its limitations (*16*, *18*). The IAM framework allows us to explore the effect of a wide range of mitigation levels on the potential for exceeding a policy-important threshold such as DAI. We do not recommend that our quantitative results be taken literally, but we suggest that our probabilistic framework and methods be taken seriously. They produce general conclusions that are more robust than estimates made with a limited set of scenarios or without probabilistic presentations of outcomes, and our threshold metric for DAI offers a risk-man-

[1]Interdisciplinary Graduate Program in Environment and Resources, [2]Department of Biological Sciences and Center for Environmental Science and Policy, Stanford University, Stanford, CA 94305, USA.

*To whom correspondence should be addressed. E-mail: mikemas@stanford.edu

agement framework for discussion of future climate change that can be applied to results at all levels of model complexity.

To define our metric for DAI, we estimated a CDF based on the Intergovernmental Panel on Climate Change (IPCC) "Reasons for Concern" (*3*) (Fig. 1). Each column in the figure represents a reason for concern about climate change in this century, on the basis of dozens of IPCC lead authors' examination of climate impacts literature, thus representing a consensus estimate of DAI. We constructed our CDF by assigning data points at the threshold temperature above which each column becomes red (Fig. 1, solid black line) and assumed that the probability of DAI increases cumulatively at each threshold temperature by a quintile, making the first threshold the 20th percentile (20‰) (*19*). This CDF is a starting point for our analysis of DAI; it facilitates a concrete sensitivity analysis at various thresholds of dangerous climate change. The median, 50‰ threshold for DAI in Fig. 1, DAI[50‰], is 2.85°C (*20*).

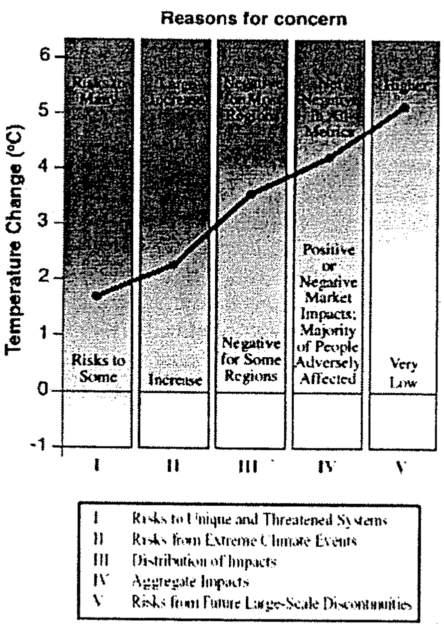

Fig. 1. An adaptation of the IPCC Reasons for Concern figure (*3*), with the thresholds used to generate our CDF for DAI. The IPCC figure conceptualizes five reasons for concern, mapped against climate change through 2100. As temperature increases, colors become redder: White indicates neutral or small negative or positive impacts or risks, yellow indicates negative impacts for some systems, and red means negative impacts or risks that are more widespread and/or greater in magnitude. The risks of adverse impacts from climate change increase with the magnitude of change, involving more of the reasons for concern. For simplicity, we use the transition-to-red thresholds for each reason for concern to construct a CDF for DAI, assuming the probability of DAI increases by a quintile as each threshold is reached (*19*).

We applied this metric for DAI to a spectrum of results based on uncertainty in three key social and natural model parameters—climate sensitivity, climate damages, and discount rate. We focused on these parameters because they are critical determinants of the policy implications of global climate change. Climate sensitivity—the equilibrium surface temperature increase from a doubling of atmospheric CO_2—determines the magnitude of anthropogenic temperature change from a given radiative forcing. The impact of this change is determined by the severity of climate damages from a given global average temperature change, usually reported as a loss of gross economic product. Both factors cannot be determined with high confidence because of the complexity of the system, missing data, and competing frameworks for analysis (*21*). In an IAM, future costs and benefits are compared by discounting their future value at some discount rate. Modeled policy responses to global climate change, where mitigation costs come long before sizeable benefits from avoided climate damages, are very sensitive to this rate. Sensitivity analysis, where uncertain parameters are varied across a likely range of values, is often used to identify and report ranges of uncertainty. When it is possible to define a probability distribution for the uncertain parameter(s), a second method—Monte Carlo (MC) analysis—can expand on a sensitivity analysis by assigning a proba-

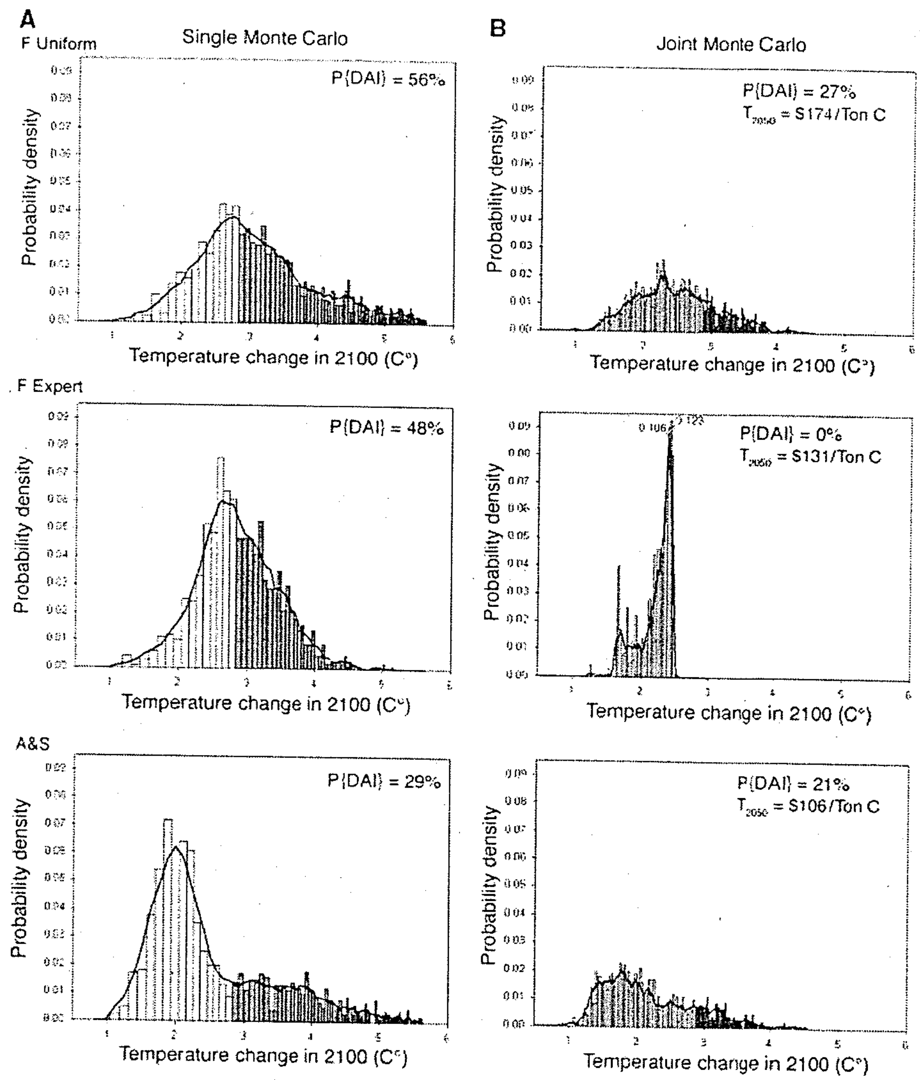

Fig. 2. (**A**) Probability distributions for each climate sensitivity distribution for the climate sensitivity–only MC analyses with zero damages and 0% PRTP (a ~1% discount rate). (**B**) Probability distributions for the joint (climate sensitivity and climate damage) MC analyses. All distributions display a 3-bin running mean and the percentage of outcomes above our median threshold of 2.85°C for dangerous climate change, P{DAI[50‰]}. The joint distributions display carbon taxes calculated in 2050 (T_{2050}) by the DICE model, using the median climate sensitivity from each climate sensitivity distribution and the median climate damage function for the joint Monte Carlo cases (*19*). When we compare the joint cases with climate policy controls (B) to the climate sensitivity–only cases without climate policy controls (A), sufficient carbon taxes reduce the potential (significantly in two out of three cases) for DAI[50‰].

bility distribution to model outcomes run as the parameter is varied. We combined both techniques to evaluate the potential for DAI (*19*).

Using general circulation models, the IPCC has long estimated the climate sensitivity to lie somewhere between 1.5°C and 4.5°C (*22*), without indicating the relative probability within this range. Other analyses produce both higher and lower values (*19*). Recent studies produce distributions wider than the IPCC range, with significant probability of climate sensitivity above 4.5°C. We used three such probability distributions: the combined distribution from Andronova and Schlesinger (A&S) (*23*), and the expert prior (F Expert) and uniform prior (F Uniform) distributions from Forest *et al.* (*24*).

In the DICE model, a climate damage function specifying the economic damages from global temperature increase is one of the important linkages between the modeled social and natural systems. We sampled from the probability distributions of Roughgarden and Schneider (*18*), based on an expert elicitation of a much broader range of climate damage functions than in the original DICE model. We used these probability distributions and those for climate sensitivity to conduct MC analyses with the DICE model (*19*). Specification of the third uncertain parameter we considered, the discount rate, has a strong normative component, with a variety of defended options (supporting online text). To prevent a high discount rate from masking variation in model results because of variation in other uncertain parameters (supporting online text), we set the pure rate of time preference (PRTP) to 0%—corresponding to a discount rate of roughly 1%—and performed a sensitivity analysis (*19*). This discount rate falls within the currently debated range, at the lower end (supporting online text).

We examined two types of model output under different assumption sets of the parameters we varied: global average surface temperature change in 2100 (*25*), which we used to evaluate the potential for DAI (*12*); and "optimal" carbon taxes (*26*), which we used to evaluate the magnitude of induced climate policy controls.

We first considered climate sensitivity uncertainty, performing three MC analyses—sampling from each climate sensitivity probability distribution separately (*19*)—without mitigation policy (to ensure that variation in results are from variation in climate sensitivity). We produced probability distributions for global temperature increase in 2100 (Fig. 2A) and indicate the percentage of outcomes that result in temperature increases above DAI[50‰]. The differences in the probability distributions of Fig. 2A show how the range of uncertainty still present among probability estimates of climate sensitivity cascade to uncertainty in our estimates for temperature change in 2100. In all three, a significant percentage of outcomes falls above DAI[50‰] (dark gray).

We introduced climate policy controls by performing a joint MC analysis of temperature increase in 2100, varying both climate sensitivity and the climate damage function (*19*), again indicating the percentage of DAI[50‰] exceedances (Fig. 2B). With the exception of the A&S distribution, for which the single MC analysis showed relatively lower probability of DAI[50‰], the joint MC runs showed significantly lower percentages of DAI[50‰]. It may seem that the most likely outcome of the joint MC runs is a relatively low temperature increase—an optimistic result. However, low temperature change outcomes result from more stringent model-generated climate policy controls, because of the inclusion of climate damages. Time-varying median carbon taxes are more than $50/ton of C by 2010, and more than $100/ton of C by 2050 in each joint analysis. Low warming and reduced probability of DAI[50‰] are reached if carbon taxes are high, when higher climate sensitivities and higher climate damage functions sampled from their probability distributions combine to force the model "agent" to react. This policy-relevant complexity is captured through a probabilistic framework.

The analysis above only considers the median DAI[50‰] threshold; therefore, these results do not fully describe the relationship between climate policy and the potential for other thresholds for DAI. We characterized the relationship between climate policy controls and the potential for DAI by calculating a series of single MC analyses, varying climate sensitivity (as in Fig. 2A) for a range of fixed damage functions. For each damage function, ranging from the 10th through the 90th percentile of the climate damage probability distribution (*18*), we performed an MC analysis sampling from each climate sensitivity distribution. We also calculated the carbon tax in 2050 for model runs that use the median climate sensitivity of each probability distribution and the median damage function (*19*).

Averaging the results from each set of three MC analyses, we determined the probability of outcomes that exceed various DAI thresholds at a given 2050 carbon tax under the assumptions described above (*19*) (Fig. 3). Each solid line corresponds to a different percentile threshold, DAI[*X*‰], chosen from our DAI CDF (Fig. 1)—a lower percentile *X* from the CDF represents a lower temperature threshold for DAI (DAI[10‰] = 1.476°C, DAI[50‰] = 2.85°C, for example). At any DAI threshold, climate policy works: Higher carbon taxes lower the probability of considerable future temperature increase and reduce the probability of DAI. Inspecting the median threshold, DAI[50‰] (Fig. 3, thick black line), indicates that a carbon tax by 2050 of $150 to $200 per ton of C reduces the probability of DAI[50‰] from ~45% without climate policy controls to nearly zero (*27*).

Finally, we demonstrated the effect of varying the discount rate. As before, we ran MC analyses varying climate sensitivity, but at different values for PRTP and with the climate damage function fixed at the median level (*19*). A higher PRTP increases the discount rate, implying that future climate damages are valued less and calculated policies will be weaker. Averaging over the outcomes for each climate sensitivity distribution, we determined the relationship between the discount rate and the probability of DAI at different temperature threshold levels (Fig. 4). As expected, increasing the discount rate shifts higher the probability distri-

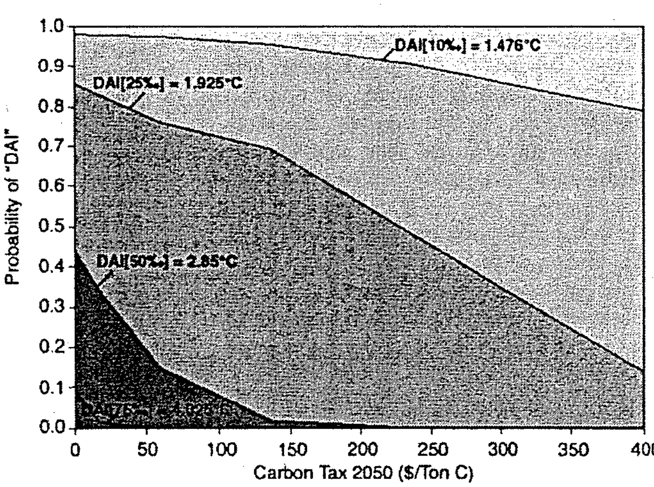

Fig. 3. The modeled relationship between carbon taxes in 2050 (a proxy for general climate policy controls) and the probability of DAI in 2100 (*19*). Each color band represents a different percentile range from the DAI threshold CDF—a lower percentile from the CDF representing a lower temperature threshold for DAI, as indicated. The solid lines indicate the percentage of outcomes exceeding the stated threshold for DAI[*X*‰], where *X* is the percentile from the DAI CDF derivable from Fig. 1, for any given level of climate policy controls. At any DAI[*X*‰] threshold, climate policy controls significantly reduce the probability of DAI, and at the median DAI[50‰] threshold (thicker black line), a 2050 carbon tax of >$150/ton of C is the model-dependent result necessary to reduce the probability of DAI from ~45% to near zero. [With a 3% PRTP, this carbon tax is an order of magnitude less and the reduction in DAI is on the order of 10% (*27*).]

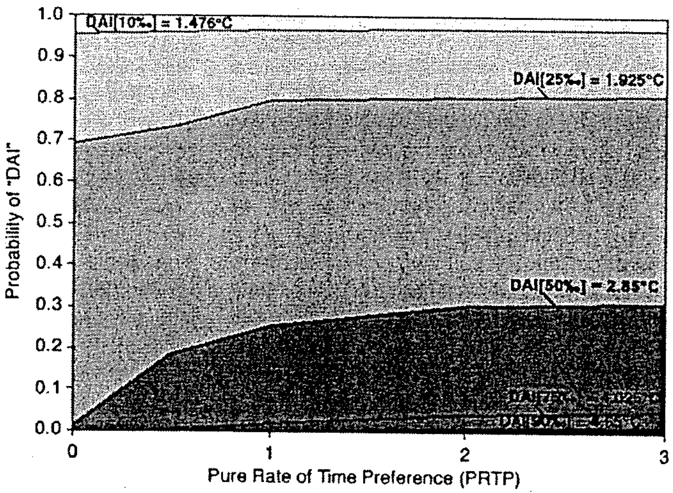

Fig. 4. The modeled relationship between the PRTP—a factor determining the discount rate—and the probability of DAI in 2100 (*19*). Increasing the PRTP (and therefore the discount rate) reduces the present value of future climate damages and increases the probability of DAI[*X*‰] as indicated, where *X* is the percentile from the DAI CDF derivable from Fig. 1. The solid lines indicate the percentage of outcomes above the stated threshold for DAI[*X*‰] for any given level of PRTP or DAI percentile threshold *X*. At our median threshold DAI[50‰] (thicker black line), the probability of DAI[50‰] rises from near zero with a 0% PRTP to 30% with a 3% PRTP, as originally specified in the DICE model.

bution of future temperature increase—a lower level of climate policy controls becomes "optimal" and thus increases the probability of DAI. At DAI[50‰] (Fig. 4, thick black line), the probability rises from near zero with a 0% PRTP to 30% with a 3% PRTP, as specified in the original DICE model. It is also clear that at PRTP values higher than 1%, the "optimal" outcome becomes increasingly insensitive to variation in future climate damages driven by variation in climate sensitivity.

The DICE model is a highly simplified representation of the climate and the economy, and its specific predictions for temperature increase or carbon tax are subject to considerable uncertainty (*28*). Although it cannot provide high-confidence quantitative answers, it is a transparent model for examining trends and processes, and its qualitative insights should be considered seriously. We present our probability distributions for future climate change to demonstrate three issues: (i) Very different levels are possible for the probability of DAI depending on its definition. (ii) Regardless of its definition, conventional climate policy controls would bring about significant reduction in the probability of DAI. (iii) This probabilistic framework is an effective method for conceptualizing climate change policy decisions.

We chose to create a CDF for DAI based on one plausible interpretation of IPCC work. In certain regions and for certain sectors, different groups might set thresholds for DAI at very different levels. Selection of that threshold can only be made through a decision-making process that combines social and natural assessments, evaluates the effects of climate change and their likelihood, and incorporates value judgments on inherent trade-offs. However, our research shows that regardless of the threshold for DAI, climate policy will reduce the likelihood of exceeding that threshold, and we suggest that this is an effective way to present model results and to demonstrate the value of climate policy, in risk-management terms that policymakers often employ.

Uncertainty in future states of natural and social systems will never be completely removed until future events are directly observed. This unalterable fact requires societies wishing to assess and influence future trends to act on the best current knowledge in the face of uncertainty. We believe that a probabilistic framework—probability distributions and risk diagrams such as Fig. 3—are an effective representation of state-of-the-art results of scientific assessments and should be understood by a wide audience, including policymakers. Policymakers have considerable experience dealing with uncertainty and risk management. For example, "acceptable risk" thresholds for nuclear power, cancer, vehicular safety, etc., are commonplace, even if controversial. The probability of DAI in many of the scenarios we discuss is far higher (by tens of percent) than the "accepted" threshold in some of these fields (though, of course, the dangers are all different). Thus, this research suggests a clear message: It is possible that some thresholds for dangerous anthropogenic interference with the climate system are already exceeded, and it is likely that more such thresholds are approaching. Despite great uncertainty in many aspects of integrated assessment, prudent actions can substantially reduce the likelihood and thus the risks of dangerous anthropogenic interference.

References and Notes

1. United Nations Framework Convention on Climate Change (UNFCCC, 1992), available at www.unfccc.int.
2. A. Patwardhan, S. H. Schneider, S. M. Semenov, "Assessing the science to address UNFCCC Article 2" (IPCC Concept Paper, available at www.ipcc.ch/activity/cct3.pdf).
3. J. B. Smith *et al.*, in *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, K. S. White, Eds. (Cambridge Univ. Press, Cambridge, UK, 2001), chap. 19.
4. S. H. Schneider, *Environ. Model. Assess.* **2**, 229 (1997).
5. M. G. Morgan, M. Henrion, Eds., *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis* (Cambridge Univ. Press, New York, NY, 1990).
6. R. N. Pittock, R. N. Jones, C. D. Mitchell, *Nature* **413**, 249 (2001).
7. S. H. Schneider, B. L. Turner, H. Morehouse Garriga, *J. Risk Res.* **1**, 165 (1998).
8. A. S. Manne, R. G. Richels, *Energy J.* **16**, 1 (1995).
9. J. K. Hammitt, R. J. Lempert, M. E. Schlesinger, *Nature* **357**, 315 (1992).
10. M. D. Webster, *Energy J.* **23**, 97 (2002).
11. R. H. Moss, S. H. Schneider, in *Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC*, R. Pachauri, T. Taniguchi, K. Tanaka, Eds. (World Meteorological Organization, Geneva, 2000), pp. 33–51.
12. S. H. Schneider, *Nature* **411**, 17 (2001).
13. A. Grübler, N. Nakicenovic, *Nature* **412**, 15 (2001).
14. S. Dessai, M. Hulme, "Does climate policy need probabilities?" (Working Paper 34, Tyndall Centre, UK, 2003).
15. We do not imply preference of the optimization framework over the methods used in other studies; in truth, we openly acknowledge the flaws many have identified in the general method (*29*) and in the DICE model we use (*17*), having ourselves contributed to this literature (*16*). There are other effective frameworks for analysis, such as the "robust strategies" approach (*29*). However, as the DICE family of models does allow a quantitative opportunity to explore methods and model uncertainties explicitly, has influenced policy decisions in the past, and continues to be used, we chose to present the influence of the most current scientific information on IAM results. The main virtue of this approach is transparency through a method to reframe the diagnosis of DAI with probabilistic IAMs.
16. M. D. Mastrandrea, S. H. Schneider, *Clim. Pol.* **1**, 433 (2001).
17. W. D. Nordhaus, *Science* **258**, 1315 (1992).
18. T. Roughgarden, S. H. Schneider, *Energy Pol.* **27**, 415 (1999).
19. Materials and methods are available as supporting material on *Science* Online.
20. There are many ways that DAI could be interpreted from this figure, or from other sources. Each reason for concern could provide its own probability distribution for DAI; each reason for concern could be given its own weight based on some definition of its likelihood; or categories or metrics for assessing DAI other than those displayed could be used. The evaluation of DAI will likely be different depending on geographical location, socioeconomic standing, and ethical value system. For a first attempt at this definition, we used the simplest possibility—equal weight for all five categories. As seen in Figs. 3 and 4, we may already have committed to exceedance of a DAI[10‰] (1.476°C) threshold, as the probability of this threshold being crossed by 2100 is near unity. As the temperature increase exceeds the orange-to-red threshold of more categories, we believe a greater number of people will agree that dangerous change is occurring or will likely occur. Thus, we use all reasons for concern instead of just one, assuming equivalence of the danger from each category. We present a traceable account (*11*) of our assumptions in creating this definition (*19*), and we believe a similar account should be made each time such a definition is created by any analyst. We know of one other effort to create a CDF for dangerous climate change, presented by Wigley (*30*). Previously, Azar and Rodhe chose 2°C as their threshold for DAI (*31*), and O'Neill and Oppenheimer chose thresholds between 1° and 3°C for individual examples of DAI (*32*), without specifying ranges or percentiles in any of these cases.
21. R. H. Moss, S. H. Schneider, in *Elements of Change 1996*, S. J. Hassol, J. Katzenberger, Eds. (Aspen Global Change Institute, Aspen, CO, 1997), pp. 90–135.
22. U. Cubasch *et al.*, in *Climate Change 2001: The Scientific Basis, Summary for Policy Makers*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, UK, 2001).
23. N. G. Andronova, M. E. Schlesinger, *J. Geophys. Res.* **106**, 22605 (2001).

24. C. E. Forest, P. H. Stone, A. P. Sokolov, M. R. Allen, M. D. Webster, *Science* **295**, 113 (2001).
25. Transient temperature change in 2100 is not, in general, equilibrium change. The inertia of the climate system is such that climate change will continue long after greenhouse gas concentrations are stabilized or emissions eliminated. Some outcomes that avoid exceeding a DAI threshold until 2100 will exceed that threshold in the next century. Therefore, the time horizon of analysis will affect the potential for DAI. However, what is "dangerous" is itself a function of adaptive capacity, not a static quantity, dependent on social and economic development. So, the very threshold for any percentile *X*, DAI[*X*‰], can itself change with time and social conditions.
26. In the DICE model, carbon taxes serve as a proxy for general climate policy controls. Thus, we do not present carbon tax data as a preferred method for mitigation or a required method to produce our results. Instead, these results should be seen as a method to provide insights into coupled model behavior, using the carbon tax in DICE as a measure of the magnitude of climate policy controls.
27. Results such as this are extremely sensitive to the discount rate. For example, the increase in the climate damage function indicated above that produces a ~45% reduction in the probability of DAI[50‰] with a 0% PRTP produces a reduction of only ~10% and an order of magnitude lower "optimal" carbon tax when we used a 3% PRTP, the value employed by the original DICE model. We chose to use a 0% PRTP for Fig. 3 exactly for this reason—that using a high discount rate masks the variation in model results because of changes in parameters other than the discount rate, and observing variation in model results due to other parameters is central to our analysis.
28. We consider three of these sources of uncertainty in the three parameters we varied, but there are other important sources of uncertainty. The DICE model does not consider adaptation, as opposed to mitigation, which theoretically would shift the probability distribution for DAI to higher temperature levels. A highly adaptive society would be less likely to experience dangerous impacts, although this would not be as likely to apply to the first reason for concern, damages to natural systems. The DICE model also only considers mitigation policies for CO_2. It does not account for "knock-on" impacts of CO_2 reductions on emissions of other atmospheric substances, and it specifies a fixed path for non-CO_2 greenhouse gases. Alternative emissions pathways for non-CO_2 gases and for other anthropogenic radiative forcing agents such as aerosols would also affect the potential for DAI.
29. R. J. Lempert, M. E. Schlesinger, *Clim. Change* **45**, 387 (2000).
30. T. Wigley, *Clim. Change*, in press.
31. C. Azar, H. Rodhe, *Science* **276**, 1818 (1997).
32. B. C. O'Neill, M. Oppenheimer, *Science* **296**, 1971 (2002).
33. We thank T. Wigley, K. Kuntz-Duriseti, J. Bushinsky, and M. Hayes for constructive comments on previous drafts. Supported by the Global Change Education Program of the Department of Energy and the Interdisciplinary Graduate Program in Environment and Resources at Stanford University (M.D.M.) and by the Winslow Foundation (S.H.S.).

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Timing, Duration, and Transitions of the Last Interglacial Asian Monsoon

Daoxian Yuan,[1] Hai Cheng,[2] R. Lawrence Edwards,[2]* Carolyn A. Dykoski,[2] Megan J. Kelly,[2] Meiliang Zhang,[1] Jiaming Qing,[1] Yushi Lin,[1] Yongjin Wang,[3] Jiangyin Wu,[3] Jeffery A. Dorale,[4] Zhisheng An,[5] Yanjun Cai[5]

Thorium-230 ages and oxygen isotope ratios of stalagmites from Dongge Cave, China, characterize the Asian Monsoon and low-latitude precipitation over the past 160,000 years. Numerous abrupt changes in $^{18}O/^{16}O$ values result from changes in tropical and subtropical precipitation driven by insolation and millennial-scale circulation shifts. The Last Interglacial Monsoon lasted 9.7 ± 1.1 thousand years, beginning with an abrupt (less than 200 years) drop in $^{18}O/^{16}O$ values 129.3 ± 0.9 thousand years ago and ending with an abrupt (less than 300 years) rise in $^{18}O/^{16}O$ values 119.6 ± 0.6 thousand years ago. The start coincides with insolation rise and measures of full interglacial conditions, indicating that insolation triggered the final rise to full interglacial conditions.

The characterization of past climate is often limited by the temporal resolution, geographic coverage, age precision and accuracy, and length and continuity of available records. Among the most robust are ice core records (*1*, *2*), which characterize, among other measures of climate, the oxygen isotopic composition of precipitation. Although many such records are benchmarks, they are limited to high-latitude or high-elevation sites, which record the oxygen isotopic composition of the last fraction of atmospheric moisture remaining after transit from moisture source regions. Cave calcite also contains information about the isotopic composition of meteoric precipitation, is widespread, and can be dated with ^{230}Th methods. Thus, caves may yield well-dated, low-latitude, low-elevation records that characterize atmospheric moisture earlier in its transit from source regions. We report here on such a record of Asian Monsoon precipitation, which covers most times since the penultimate glacial period, about 160 thousand years ago (ka).

We have previously reported a cave oxygen isotope record of the East Asian Monsoon (*3*) from Hulu Cave, China [32°30′N, 119°10′E; elevation 100 m; cave temperature 15.7°C; mean annual precipitation $\delta^{18}O_{VSMOW}$ = −8.4 per mil (‰) (VSMOW, Vienna standard mean ocean water); and mean annual precipitation 1036 mm] (table S1), covering the last glacial period [75 ka to 10 thousand years (ky) before the present]. We now report similar data from Dongge Cave, China, 1200 km WSW of Hulu Cave, a site affected by the Asian Monsoon. The Dongge record more than doubles the time range covered in the Hulu record and overlaps the Hulu record for ~35 ky, allowing comparison between sites. Highlights include the timing and rapidity of the onset (*4*) and end of the Last Interglacial Asian Monsoon and the degree of Last Interglacial Monsoon variability.

Dongge Cave is 18 km SE of Libo, Guizhou Province (25°17′N, 108°5′E), at an elevation of 680 m. The cave temperature (15.6°C), mean annual $\delta^{18}O$ of precipitation (−8.3‰), and seasonal changes in precipitation and $\delta^{18}O$ of precipitation are similar to those at Hulu, with mean annual precipitation being higher (1753 mm) (table S1). Stalagmites D3 and D4 were collected ~100 m below the surface, 300 and 500 m from the entrance, in the 1100-m-long main passageway. D3 is 210 cm and D4 is 304 cm long, with the diameters of each varying between 12 and 20 cm. Stalagmites were halved vertically and drilled along growth axes to produce subsamples for oxygen isotope analysis (*5*) and ^{230}Th dating by thermal ionization (*6*, *7*) and inductively coupled plasma mass spectroscopy (*8*). Sixty-six ^{230}Th dates from D3 and D4 (table S2) and 10 dates from Hulu Cave stalagmite H82 (table S3), all in stratigraphic order, have 2σ analytical errors of ±80 years at 10 ky and ±1 ky at 120 ky. Six hundred and forty $\delta^{18}O$ measurements have spatial resolution corresponding to 20 years to 2 ky for different portions of D3 and D4

[1]Karst Dynamics Laboratory, Ministry of Land and Resources, 40 Qixing Road, Guilin 541004, China. [2]Department of Geology and Geophysics, University of Minnesota, Twin Cities, MN 55455, USA. [3]College of Geography Science, Nanjing Normal University, Nanjing 210097, China. [4]Department of Geoscience, University of Iowa, Iowa City, IA 52242, USA. [5]State Key Lab of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China.

*To whom correspondence should be addressed. E-mail: edwar001@umn.edu

tral case). For the CE commitment, sea level rises at about 25 cm/century (uncertainty range, 7 to more than 50 cm/century). The fractions arising from unforced contributions to sea level rise are less than those in the CC case.

The CE results reinforce the common knowledge that, in order to stabilize global-mean temperatures, we eventually need to reduce emissions of greenhouse gases to well below present levels (*21*). The CC results are potentially more alarming, because they are based on a future scenario that is clearly impossible to achieve and so represent an extreme lower bound to climate change over the next few centuries. For temperature, they show that the inertia of the climate system alone will guarantee continued warming and that this warming may eventually exceed 1°C. For sea level, a continued rise of about 10 cm/century for many centuries is the best estimate. Although such a slow rate may allow many coastal communities to adapt, profound long-term impacts on low-lying island communities and on vulnerable ecosystems (such as coral reefs) seem inevitable.

References and Notes

1. M. L. Hoffert, A. J. Callegari, C.-T. Hsieh, *J. Geophys. Res.* **86**, 6667 (1980).
2. J. Hansen *et al.*, *Science* **229**, 857 (1985).
3. T. M. L. Wigley, M. E. Schlesinger, *Nature* **315**, 649 (1985).
4. T. M. L. Wigley, *Climate Monitor* **13**, 133 (1984).
5. R. T. Wetherald, R. J. Stouffer, K. W. Dixon, *Geophys. Res. Lett.* **28**, 1535 (2001).
6. T. M. L. Wigley, S. C. B. Raper, in *Climate and Sea Level Change: Observations, Projections and Implications*, R. A. Warrick, E. M. Barrow, T. M. L. Wigley, Eds. (Cambridge Univ. Press, Cambridge, 1993), pp. 111–133.
7. R. J. Stouffer, S. Manabe, *J. Clim.* **12**, 2224 (1999).
8. J. Hansen *et al.*, *J. Geophys. Res.* **107**, 4347, 10.1029/2001JD001143 (2002).
9. R. A. Pielke Sr., *Bull. Am. Met. Soc.* **84**, 331 (2003).
10. T. M. L. Wigley, S. C. B. Raper, *Science* **293**, 451 (2001).
11. S. C. B. Raper, T. M. L. Wigley, R. A. Warrick, in *Sea-Level Rise and Coastal Subsidence: Causes, Consequences and Strategies*, J. Milliman, B. U. Haq, Eds. (Kluwer Academic Publishers, Dordrecht, Netherlands, 1996), pp. 11–45.
12. T. M. L. Wigley, S. C. B. Raper, *J. Clim.* **15**, 2945 (2002).
13. U. Cubasch, G. A. Meehl, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 525–582.
14. S. C. B. Raper, J. M. Gregory, T. J. Osborn, *Clim. Dyn.* **17**, 601 (2001).
15. Materials and methods are available as supporting material on *Science* Online.
16. J. A. Church, J. M. Gregory, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 639–693.
17. T. M. L. Wigley, S. C. B. Raper, *Geophys. Res. Lett.*, in press.
18. J. Lean, J. Beer, R. Bradley, *Geophys. Res. Lett.* **22**, 3195 (1995).
19. C. M. Ammann, G. A. Meehl, W. M. Washington, C. S. Zender, *Geophys. Res. Lett.* **30**, 1657, 10.1029/2003GL016875 (2003).
20. This is a sensitivity study and not a probabilistic analysis. Simplistically, if the high climate sensitivity and low forcing extremes are independent and each has a probability of exceedance of 0.05, the probability of both being exceeded is 0.0025. Further constraints may be placed by comparing model simulations with observed climate changes over the past century (*22*).
21. T. M. L. Wigley, R. Richels, J. A. Edmonds, *Nature* **379**, 240 (1996).
22. C. E. Forest, P. H. Stone, A. P. Sokolov, M. R. Allen, M. D. Webster, *Science* **295**, 113 (2002).

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Tables S1 and S2

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How Much More Global Warming and Sea Level Rise?

Gerald A. Meehl,* Warren M. Washington, William D. Collins, Julie M. Arblaster, Aixue Hu, Lawrence E. Buja, Warren G. Strand, Haiyan Teng

Two global coupled climate models show that even if the concentrations of greenhouse gases in the atmosphere had been stabilized in the year 2000, we are already committed to further global warming of about another half degree and an additional 320% sea level rise caused by thermal expansion by the end of the 21st century. Projected weakening of the meridional overturning circulation in the North Atlantic Ocean does not lead to a net cooling in Europe. At any given point in time, even if concentrations are stabilized, there is a commitment to future climate changes that will be greater than those we have already observed.

Increases of greenhouse gases (GHGs) in the atmosphere produce a positive radiative forcing of the climate system and a consequent warming of surface temperatures and rising sea level caused by thermal expansion of the warmer seawater, in addition to the contribution from melting glaciers and ice sheets (*1*, *2*). If concentrations of GHGs could be stabilized at some level, the thermal inertia of the climate system would still result in further increases in temperatures, and sea level would continue to rise (*2–9*). We performed multimember ensemble simulations with two global coupled three-dimensional climate models to quantify how much more global warming and sea level rise (from thermal expansion) we could experience under several different scenarios.

The Parallel Climate Model (PCM) has been used extensively for climate change experiments (*10–15*). This model has a relatively low climate sensitivity as compared to other models, with an equilibrium climate sensitivity of 2.1°C and a transient climate response (TCR) (the globally averaged surface air temperature change at the time of CO_2 doubling in a 1% CO_2 increase experiment) of 1.3°C. The former is indicative of likely atmospheric feedbacks in the model, and the latter includes ocean heat uptake and provides an indication of the transient response of the coupled climate system (*6*, *12*). A second global coupled climate model is the newly developed Community Climate System Model version 3 (CCSM3), with higher horizontal resolution (atmospheric gridpoints roughly every 1.4° as compared to the PCM, with gridpoints about every 2.8°) and improved parameterizations in all components of atmosphere, ocean, sea ice, and land surface (*16*). The CCSM3 has somewhat higher sensitivity, with an equilibrium climate sensitivity of 2.7°C and TCR of 1.5°C. Both models have about 1° ocean resolution (0.5° in the equatorial tropics), with dynamical sea ice and land surface schemes. These models were run for four- and eight-member ensembles for the PCM and CCSM3, respectively, for each scenario (except for five members for A2 in CCSM3).

The 20th-century simulations for both models include time-evolving changes in forcing from solar, volcanoes, GHGs, tropospheric and stratospheric ozone, and the direct effect of sulfate aerosols (*14*, *17*). Additionally, the CCSM3 includes black carbon distributions scaled by population over the 20th century, with those values scaled by sulfur dioxide emissions for the rest of the future climate simulations. The CCSM3 also uses a different solar forcing data set for the 20th century (*18*). These 20th-century forcing differences between CCSM3 and PCM are not thought to cause large differences in response in the climate change simulations beyond the year 2000.

The warming in both the PCM and CCSM3 is close to the observed value of about 0.6°C for the 20th century (*19*), with PCM warming 0.6°C and CCSM3 warming 0.7° (averaged over the period 1980–1999 in relation to 1890–1919). Sea level rises are 3 to 5 cm, respectively, over the 20th century as com-

National Center for Atmospheric Research, Post Office Box 3000, Boulder, CO 80307, USA.

*To whom correspondence should be addressed. E-mail: meehl@ncar.ucar.edu

pared to the observed estimate of 15 to 20 cm. This lower value from the models is consistent with the part of 20th-century sea level rise thought to be caused by thermal expansion (*20*, *21*), because as the ocean warms, seawater expands and sea level rises. Neither model includes contributions to sea level rise due to ice sheet or glacier melting. Partly because of this, the sea level rise calculations for the 20th century from the models are probably at least a factor of 3 too small (*20*, *21*). Therefore, the results here should be considered to be the minimum values of sea level rise. Contributions from future ice sheet and glacier melting could perhaps at least double the projected sea level rise produced by thermal expansion (*1*).

Atmospheric CO_2 is the dominant anthropogenic GHG (*22*), and its time evolution can be used to illustrate the various scenarios (Fig. 1A). The three Special Report for Emissions Scenarios (SRES) show low (B1), medium (A1B), and high (A2) increases of CO_2 over the course of the 21st century. Three stabilization experiments were performed: one with concentrations of all constituents held constant at year 2000 values and two (B1 and A1B) with concentrations held constant at year 2100 values. Although these are idealized stabilization experiments, it would take a significant reduction of emissions below 1990 values within a few decades and within about a century to achieve stabilized concentrations in B1 and A1B, respectively (*23*).

Even if we could have stopped any further increases in all atmospheric constituents as of the year 2000, the PCM and CCSM3 indicate that we are already committed to 0.4° and 0.6°C, respectively, more global warming by the year 2100 as compared to the 0.6°C of warming observed at the end of the 20th century (Table 1 and Fig. 1B). (The range of the ensembles for the climate model temperature anomalies here and to follow is about ±0.1°C.) But we are already committed to proportionately much more sea level rise from thermal expansion (Fig. 1C).

At the end of the 21st century, as compared to the end of the 20th century (1980–1999 base period), warming in the low-estimate climate change scenario (SRES B1) is 1.1° and 1.5°C in the two models (Table 1 and Fig. 1B), with sea level rising to 13 and 18 cm above year 1999 levels. The spread among the ensembles for sea level in all cases amounts to less than ±0.3 cm. A medium-range scenario (SRES A1B) produces a warming at the end of the 21st century of 1.9° and 2.6°C, with about 18 and 25 cm of sea level rise in the two models. For the high-estimate scenario (A2), warming at 2100 is about 2.2° and 3.5°C, and sea level rise is 19 and 30 cm. The range of transient temperature response in the two models for the 20th century through the mid-21st century is considerably less than the range in their equilibrium climate sensitivities (Table 1) due in part to less than doubled CO_2 forcing as well as ocean heat uptake characteristics (*24*). Thus, our confidence in model simulations of 20th-century climate change and projections for much of the 21st century (as represented by the range

Fig. 1. (A) Time series of CO_2 concentrations for the various scenarios. (B) Time series of globally averaged surface air temperatures from the PCM and CCSM3. (C) Same as (B), except that sea level rise comes from thermal expansion only. In (C), the control drift is first subtracted from each experiment, and then in (B) and (C), the base period for calculating anomalies is 1980–1999. Solid lines are ensemble means, and shading indicates the range of ensemble members. Line identifiers for the various scenarios and the two models are given in each panel.

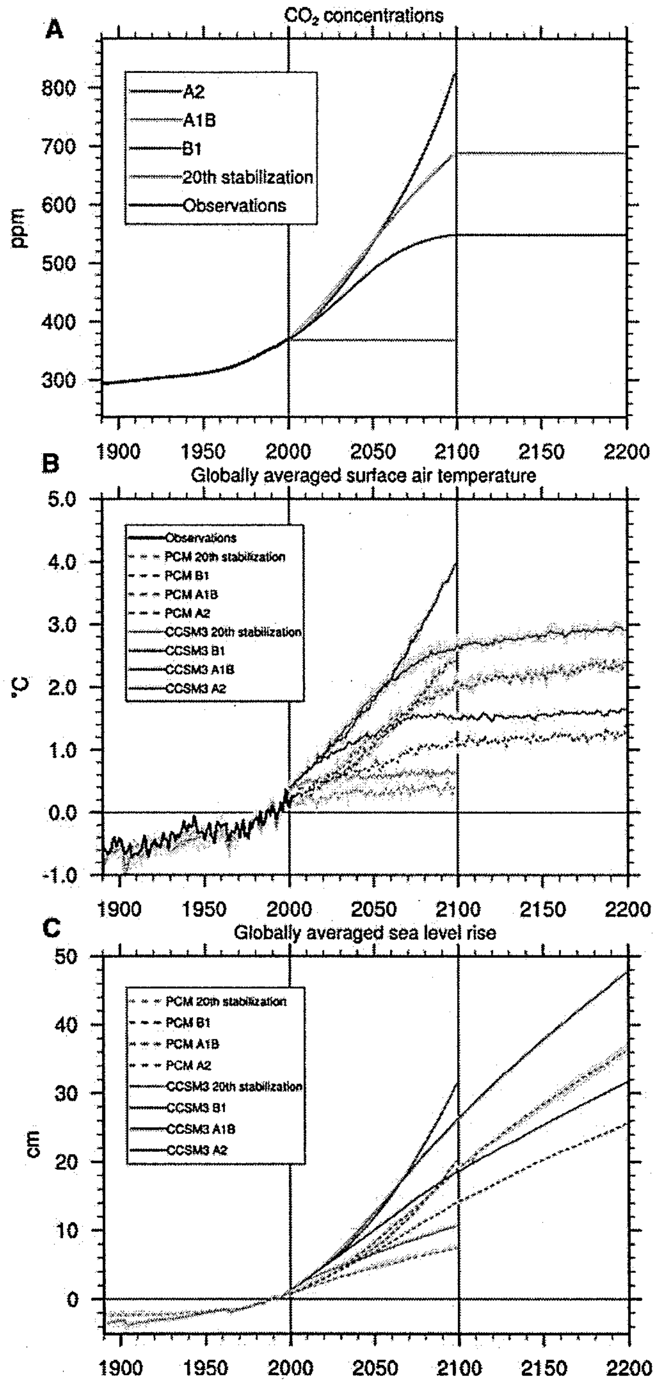

Table 1. Globally averaged surface temperature differences (in °C) comparing equilibrium climate sensitivity from the two models with simulated warming for the 20th century, mid-21st century, and late 21st century for the different experiments. Midcentury differences are calculated for 2041–2060 minus 1980–1999, and late century differences are for 2080–2099 minus 1980–1999. A2 at 2100 has more than double present-day CO_2 amounts (Fig. 1A).

Model	Equilibrium sensitivity	20th century	2050 stabilized	2050 B1	2050 A1B	2050 A2	2100 stabilized	2100 B1	2100 A1B	2100 A2
PCM	2.1	0.6	0.3	0.7	1.2	1.1	0.4	1.1	1.9	2.2
CCSM3	2.7	0.7	0.6	1.2	1.9	1.8	0.6	1.5	2.6	3.5

in the transient response of the models) is considerably better than that represented by the larger uncertainty range of the equilibrium climate sensitivity among the models.

If concentrations of all GHGs and other atmospheric constituents in these simulations are held fixed at year 2100 values, we would be committed to an additional warming by the year 2200 for B1 of about 0.1° to 0.3°C for the models (Fig. 1B). This small warming commitment is related to the fact that CO_2 concentrations had already started to stabilize at about 2050 in this scenario (Fig. 1A). But even for this small warming commitment in B1, there is almost double the sea level rise seen over the course of the 21st century by 2200, or an additional 12 and 13 cm (Fig. 1C). For A1B, about 0.3°C of additional warming occurs by 2200, but again there is roughly a doubling of 21st-century sea level rise by the year 2200, or an additional 17 and 21 cm. By 2300 (not shown), with concentrations still held at year 2100 values, there would be less than another 0.1°C of warming in either scenario, but yet again about another doubling of the committed sea level rise that occurred during the 22nd century, with additional increases of 10 and 18 cm from thermal expansion for the two models for the stabilized B1 experiment, and 14 and 21 cm for A1B as compared to year 2200 values. Sea level rise would continue for at least two more centuries beyond 2300, even with these stabilized concentrations of GHGs (*2*).

The meridional overturning maximum in the North Atlantic, indicative of the thermohaline circulation in the ocean, is stronger in the preindustrial simulation in the PCM (32.1 sverdrups) compared to the CCSM3 (21.9 sverdrups), with the latter closer to observed estimates that range from 13 to 20 sverdrups (*25–27*). The mean strength of the meridional overturning and its changes are an indication of ocean ventilation, and they contribute to ocean heat uptake and consequent time scales of temperature response in the climate system (*12*, *24*, *28*).

The model with the higher sensitivity (CCSM3) has the greater temperature and sea level rise response at the year 2100 for the B1, A1B, and A2 scenarios (Fig. 1, B and C) and also the larger decrease in meridional overturning in the North Atlantic (–4.0, –5.3, and –6.2 sverdrups or –18, –24, and –28%, respectively) as compared to the model that is less sensitive (PCM), with the lower forced response for B1, A1B, and A2 with decreases of meridional overturning in the Atlantic that are about a factor of 2 less (–1.0, –3.5, and –4.5 sverdrups, or –3, –11, and –14%, respectively). This is consistent with the idea that a larger percentage decrease in meridional overturning would be associated with greater ocean heat uptake and greater surface temperature warming (*12*, *24*).

The warming commitment for 20th-century forcing held fixed at year 2000 values is larger in the CCSM3 than in the PCM (0.6° versus 0.4°C). This is also consistent with the recovery of the meridional overturning in the 21st century after concentrations are stabilized in the PCM (net recovery of +0.2 sverdrups) compared to the CCSM3 (meridional overturning continues to weaken by –0.3 sverdrups before a modest recovery).

Therefore, the PCM, with less climate sensitivity and lower TCR but with greater mean meridional overturning in the Atlantic, has less reduction of North Atlantic meridional overturning and less forced response. The meridional overturning recovers more quickly in the PCM, contributing to even less warming commitment after concentrations are stabilized at year 2000 values. On the other hand, the CCSM3, with higher sensitivity and weaker mean meridional overturning, has a larger reduction of meridional overturning due to global warming (and particularly a larger percent decrease of meridional overturning) than the PCM and contributes to more warming commitment for GHG concentrations stabilized at year 2000 values.

The processes that contribute to these different warming commitments involve small radiative flux imbalances at the surface (on the order of several tenths of a watt per square meter) after atmospheric GHG concentrations are stabilized. This small net heat flux into the ocean is transferred to the deeper layers through mixing, convection, and ventilation processes such as the meridional overturning circulation that connects the Northern and Southern Hemisphere high-latitude deep

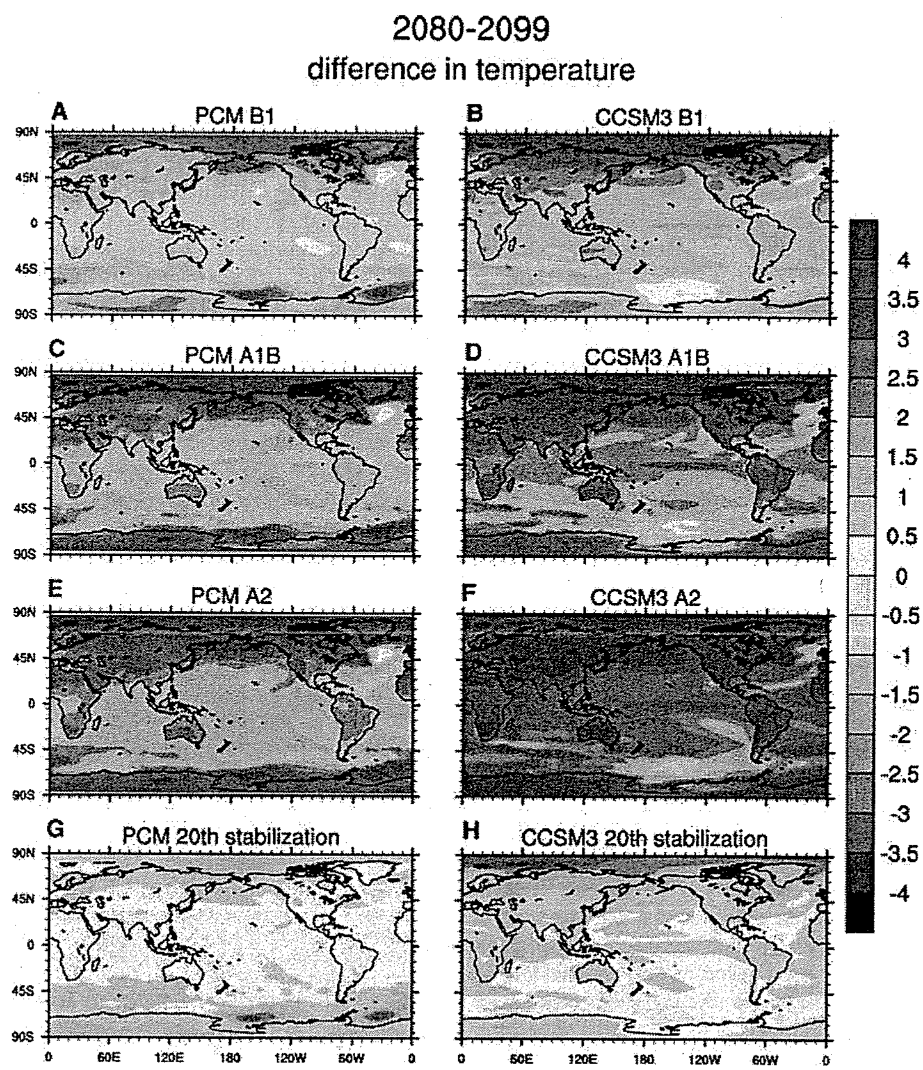

Fig. 2. Surface temperature change for the end of the 21st century (ensemble average for years 2080–2099) minus a reference period at the end of the 20th century (ensemble average for years 1980–1999) from 20th-century simulations with natural and anthropogenic forcings. (**A**) The PCM for the B1 scenario. (**B**) The CCSM3 for the B1 scenario. (**C**) The PCM for the A1B scenario. (**D**) The CCSM3 for the A1B scenario. (**E**) The PCM for the A2 scenario. (**F**) The CCSM3 for the A2 scenario. (**G** and **H**) Temperature commitment for GHG concentrations stabilized at year 2000 values; ensemble average for years 2080–2099 minus a reference period ensemble average for years 1980–1999 from 20th-century simulations. More than 95% of the values in each panel are significant at the 10% level from a Student's *t* test, and a similar proportion exceed 1 SD of the intraensemble standard deviations.

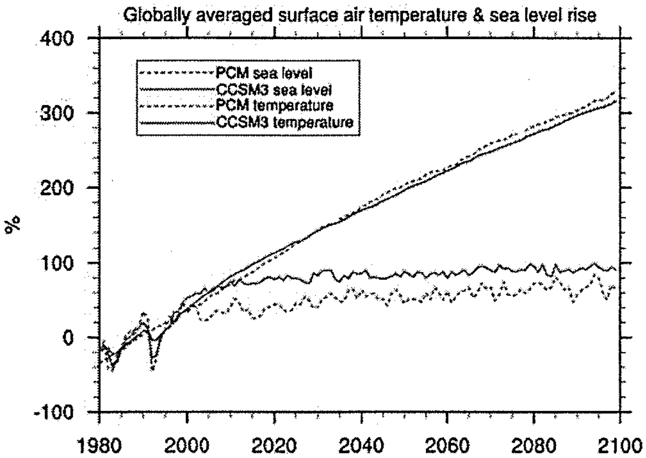

Fig. 3. Ensemble mean percent increase of globally averaged surface air temperature and sea level rise from the two models computed relative to values for the base period 1980–1999 for the experiment in which GHG concentrations and all other atmospheric constituents were stabilized at the end of the 20th century.

ocean circulations (*29*). Thus, in addition to changes in the meridional overturning circulation, the strength of the mean circulation also plays a role (*12*, *24*, *28*). The temperature difference between the upper and lower branches of the Atlantic meridional overturning circulation is smaller in the PCM than in the CCSM3 because of the stronger rate of mean meridional overturning in the PCM that induces a greater heat exchange or ventilation between the upper and deeper ocean. In the PCM, recovery of the meridional overturning is more rapid in the 21st century, thus producing even greater mixing and less warming commitment, whereas the CCSM3 recovers more slowly, with greater warming commitment by the year 2200 and on to 2300.

Geographic patterns of warming (Fig. 2) show more warming at high northern latitudes and over land, generally larger-amplitude warming in the CCSM3 as compared to the PCM, and geographic temperature increases roughly proportional to the amplitude of the globally averaged temperature increases in the different scenarios (Fig. 1B). Slowdowns in meridional overturning in the respective models (which are greater percentage-wise in the CCSM3 than the PCM) are not characterized by less warming over northern Europe in either model. The warming produced by increases in GHGs overwhelms any tendency toward decreased high-latitude warming from less northward heat transport by the weakened meridional overturning circulation in the Atlantic. There is more regional detail in the higher-resolution CCSM3 as compared to the PCM, with an El Niño–like response (*30*) in the equatorial Pacific (greater warming in the equatorial central and eastern Pacific than in the western Pacific) in the CCSM3 as compared to the PCM. This is related to cloud feedbacks in the CCSM3 involving the improved prognostic cloud liquid water scheme, as compared to the diagnostic cloud liquid water formulation in the PCM (*31*).

The warming commitment from the 20th-century stabilization experiments (Fig. 2, bottom) shows the same type of pattern in the forced experiments, with greater warming over high latitudes and land areas. For regions such as much of North America, even after stabilizing GHG concentrations, we are already committed to more than an additional half a degree of warming in the two models. The pattern of the 20th-century stabilization experiments is similar to those produced in the 21st-century stabilization experiments with A1B and B1 (not shown).

Though temperature increase shows signs of leveling off 100 years after stabilization, sea level continues to rise unabated with proportionately much greater increases compared to temperature, with these committed increases over the 21st century more than a factor of 3 greater, percentage-wise, for sea level rise (*32*) than for temperature change (Fig. 3). Thus, even if we could stabilize concentrations of GHGs, we are already committed to significant warming and sea level rise no matter what scenario we follow. These results confirm and quantify earlier studies with simple and global models in that the sea level rise commitment is considerably more than the temperature change commitment.

References and Notes

1. J. A. Church *et al.*, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 639–693.
2. T. M. L. Wigley, *Science* **307**, 1766 (2005).
3. J. F. B. Mitchell *et al.*, *Geophys. Res. Lett.* **27**, 2977 (2000).
4. F. P. Bretherton *et al.*, in *Climate Change: The IPCC Scientific Assessment*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 1990), pp. 173–194.
5. A. Kattenberg *et al.*, in *Climate Change 1995: The Science of Climate Change*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 1995), pp. 285–357.
6. U. Cubasch *et al.*, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 525–582.
7. R. T. Wetherald *et al.*, *Geophys. Res. Lett.* **28**, 1535 (2001).
8. T. M. L. Wigley, S. Raper, in *Climate and Sea Level Change: Observations, Projections and Implications*, R. A. Warrick *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2003), pp. 111–133.
9. R. J. Stouffer, S. Manabe, *J. Clim.* **12**, 2224 (1999).
10. W. M. Washington *et al.*, *Clim. Dyn.* **16**, 755 (2000).
11. G. A. Meehl *et al.*, *Clim. Dyn.* **17**, 515 (2001).
12. G. A. Meehl *et al.*, *J. Clim.* **17**, 1584 (2004).
13. G. A. Meehl *et al.*, *Clim. Dyn.* **23**, 495 (2004).
14. G. A. Meehl *et al.*, *J. Clim.* **17**, 3721 (2004).
15. G. A. Meehl, C. Tebaldi, *Science* **305**, 994 (2004).
16. For a description of the CCSM3, see www.ccsm.ucar.edu.
17. B. D. Santer *et al.*, *Science* **301**, 479 (2003).
18. The 20th-century solar forcing in the PCM is from (*33*). The 20th-century solar forcing in the CCSM3 is from (*34*).
19. C. K. Folland *et al.*, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 99–181.
20. L. Miller, B. C. Douglas, *Nature* **428**, 406 (2004).
21. J. A. Church *et al.*, *J. Clim.* **17**, 2609 (2004).
22. V. Ramaswamy, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 349–416.
23. I. C. Prentice *et al.*, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 183–237.
24. S. C. B. Raper *et al.*, *J. Clim.* **15**, 124 (2002).
25. M. M. Hall, H. L. Bryden, *Deep Sea Res.* **29**, 150 (1982).
26. D. Roemmich, C. Wunsch, *Deep Sea Res.* **32**, 619 (1985).
27. M. S. McCartney, L. D. Talley, *J. Phys. Oceanogr.* **14**, 922 (1984).
28. P. R. Gent, G. Danabasoglu, *J. Clim.* **17**, 4058 (2004).
29. A. Hu *et al.*, *J. Clim.* **17**, 4267 (2004).
30. G. A. Meehl, W. M. Washington, *Nature* **382**, 56 (1996).
31. G. A. Meehl *et al.*, *J. Clim.* **13**, 1879 (2000).
32. The sea level rise at the year 2100 in the 20th-century stabilization experiment is greater in the CCSM3 than in the PCM in Fig. 1C relative to the 1980–1999 base period, but they both have about the same percentage increase as compared to the total sea level rise that occurred during the 20th century in the respective models as depicted in Fig. 3. This is because the CCSM3 has greater total sea level rise during the 20th century than does the PCM (4.5 cm compared to 3.0 cm, respectively), partly due to the higher sensitivity of the CCSM3 as well as the comparative meridional overturning circulation processes discussed in the text.
33. D. V. Hoyt, K. H. Schatten, *J. Geophys. Res.* **98**, 18895 (1993).
34. J. Lean *et al.*, *Geophys. Res. Lett.* **107**, 10.1029/2001JD001143 (1995).

35. We acknowledge the efforts of a large group of scientists at the National Center for Atmospheric Research (NCAR), at several U.S. Department of Energy (DOE) and National Oceanic and Atmospheric Administration labs, and at universities across the United States who contributed to the development of the CCSM3 and who participated in formulating the 20th-century and future climate change simulations through the CCSM working groups on atmosphere, ocean, land surface, polar climate, climate change, climate variability, paleoclimate, biogeochemistry, and software engineering. In particular, we thank A. Middleton and V. Wayland from NCAR and M. Wehner at the National Energy Research Scientific Computing Center (NERSC) for their work in either running the model experiments or managing the massive amount of model data. The formidable quantity of supercomputer resources required for this ambitious modeling effort was made available at NCAR through the Initiative Nodes and the Climate System Laboratory and through DOE as part of its Advanced Scientific Research (ASCR). ASCR provides computing facilities at NERSC, Los Alamos National Laboratory (LANL), and the Oak Ridge National Laboratory (ORNL) Center for Computational Science. Additional simulations with the CCSM3 were performed by the Central Research Institute for the Electric Power Industry (CRIEPI), using the Earth Simulator in Japan through the international research consortium of CRIEPI, NCAR, and LANL under the Project for Sustainable Coexistence of Human Nature and the Earth of the Japanese Ministry of Education, Culture, Sports, Science and Technology. Portions of this study were supported by the Office of Biological and Environmental Research, DOE, as part of its Climate Change Prediction Program; and by the National Center for Atmospheric Research. This work was also supported in part by the Weather and Climate Impact Assessment Initiative at NCAR. NCAR is sponsored by NSF.

22 October 2004; accepted 24 January 2005
10.1126/science.1106663

m MU/

Santa Barbara County
Air Pollution Control District

Our Vision Clean Air

I UNDERSTAND BHP/CABRILLO PORT LNG W/ MEET CARB & PUC STD'S.

PLEASE RETURN TO MU

February 25, 2005

Lt. Ken Kusano (G-MSO-5)
US Coast Guard
2100 Second Street S.W.,
Washington, D.C. 20593-0001

Mr. Cy Oggins,
California State Lands Commission
100 Howe Ave., Suite 100-South,
Sacramento, CA 95825-8202

SUBJECT: SUPPLEMENTAL COMMENTS ON CABRILLO PORT DEEPWATER PORT LICENSE APPLICATION: DEIS/DEIR
Docket Number: USCG-2004-16877; State Clearinghouse Number: 2004021107

Dear Lt. Kusano and Mr. Oggins:

The Santa Barbara County Air Pollution Control District (District) provides this letter as a supplement to our comment letter, dated December 20, 2004, on the DEIS/DEIR referenced above. Our supplemental comments are based on new information of substantial importance discovered since the close of the public comment period on this project. The new information appears to be inconsistent with information provided in the DEIS/DEIR regarding the Environmental Setting of the proposed project.

The District is concerned about the potential for this project to import liquefied natural gas (LNG) that does not meet the current California Air Resources Board (CARB) specifications (i.e., LNG that contains higher BTU content levels of ethane, propane, and butane) for compressed natural gas (CNG) for use in motor vehicles. A recent study conducted by Southern California Gas Company (Gas Quality and LNG Research Study Draft Final Report dated 2-11-05) states that LNG sources originating in areas such as Indonesia, Russia, and Australia differ from natural gas currently supplied to southern California from out-of-state domestic sources as some ethane, propane and butane have been removed from out-of-state domestic natural gas prior to shipment via interstate pipelines. (An excerpt from this study is attached for your convenience.) If correct, this finding is inconsistent with Section 4.6.1 that states that the LNG to be imported for the project will meet pipeline quality specifications (including CARB specifications) without further treatment at the offshore storage and regasification unit. This conflicting information leads us to believe that the project could indeed import LNG that does not meet CARB specifications and, if so, the DEIS/DEIR should address this important issue.

The importation of LNG into southern California that does not meet California's CNG specifications creates a potential for increased regional emissions from both stationary and mobile sources. In fact, the recent Southern California Gas Company study shows a strong correlation between increased NOx emissions and higher BTU content test gases for various residential/commercial gas appliances. The DEIS/DEIR should address how this could impact existing regional emission levels. We strongly recommend that all imported LNG meet CARB motor vehicle fuel specifications for CNG in order to ensure that there are no increases in regional emissions from the importation of LNG. Further, since it appears that it is foreseeable

1BB

Terence E. Dressler Air Pollution Control Officer
260 North San Antonio Road, Suite A Santa Barbara, CA 93110 • www.sbcapcd.org 805.961.8800 805.961.8801 (fax)

that this project may import such "hot" gas, the District also believes that your commission must address the issue of whether recirculation of the DEIS/DEIR is required under CEQA.

Again, we appreciate the opportunity to comment on the DEIS/DEIR for this important project. If you need additional information on these comments please call me at 805.961.8857.

Sincerely,

Tom Murphy
Manager, Technology and Environmental Assessment

cc: TEA Chron File
Bobbie Bratz, Santa Barbara County Air Pollution Control District
William Dillon, Deputy County Counsel
Martin Kay, South Coast Air Quality Management District
Scott Johnson, Ventura County Air Pollution Control District
Alison Dettmer, California Coastal Commission

Attachment

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BACKGROUND

SCG and San Diego Gas & Electric Company (SDG&E) provide gas distribution services to approximately six million customers in southern California. The largest portion of this area's current gas supply that reaches our customers originates from the Rocky Mountains, the Permian Basin, and the San Juan Basin. A smaller portion is produced within California.

While supplies have traditionally been adequate to meet demand, a nationwide natural gas supply imbalance is developing, as new gas reserves are not being discovered and developed at a rate matching the overall increase in demand. The rapid growth in natural gas demand and a slowdown in developing new North American gas supplies have led to increased gas commodity prices. At current and projected natural gas prices, importation of natural gas, shipped as LNG, has become an economically viable option. The US Department of Energy's (DOE) "Energy Outlook 2003" projects a ten-fold increase in LNG imports from 2001 to 2025. Five west coast LNG supply projects are in various stages of development. At this time, we cannot predict which projects will initiate operation. However, we believe that LNG will provide a substantial portion of future California natural gas supplies and will access end users through new receipt points close to load centers.

Supplies of LNG for the SCG system would originate primarily from Pacific Rim countries, such as Indonesia, Russia, and Australia. The respective chemical compositions and heating values of LNG supplies from these sources differ from natural gas supplied to southern California from out-of-state domestic sources as some ethane, propane and butanes have been removed from out-of-state domestic natural gas prior to shipment via interstate pipelines. Furthermore, gas components such as CO_2, N_2, and O_2 and heavier hydrocarbon components ($>C_4$), which are common in domestic natural gas supplies, are virtually nonexistent in LNG. California-produced gas can exhibit concentrations of higher ethane and propane similar to LNG.

Completion of just one proposed LNG terminal on the West Coast could deliver from 500MMscf to a 1Bscf of natural gas into the SCG and SDG&E gas distribution systems each day, replacing gas from sources currently supplying this region. Multiple terminals could deliver much more. Thus, significant numbers of SCG and SDG&E customers' utilization equipment could experience a change in gas composition from out-of-state domestic natural gas to gas supplies from LNG. Furthermore, given the operating characteristics of the SCG/SDG&E transmission and distribution systems and customer usage patterns, many customers may be subject to "swings" in gas composition from traditional interstate supplies to new supplies or vice versa in relatively short timeframes.

SCG has actively tested appliances and small industrial/commercial equipment to monitor equipment performance over broad ranges of gas composition. Extensive testing in the laboratory and field in the mid 90's led to the establishment of an upper Btu limit for SCG's Gas Quality Standards (Rule 30). During those tests, it was noted that for a few tested appliances test results were not consistent with the interchangeability indices calculations. Subsequent testing over the next several years confirmed that some newer end-use combustion technologies, such as premix/powered combustion, yielded results that were not predictable within the conventional interchangeability indices calculations. These combustion systems, although resulting in better efficiencies and lower NOx, seem to be more sensitive to changes in gas quality and rate of change in gas quality.

Marty Kay

From: Zimpfer.Amy@epamail.epa.gov
Sent: Friday, September 16, 2005 1:48 PM
To: laura_yannayon@epamail.epa.gov; Marty Kay
Subject: Fw: BHP Billiton Cabrillo Port LNG Deepwater Port

Marty--Laura Yannayon is our lead on the q uality of gas issue. She can provide more detail and is available at 415.972.3534. Thanks

Amy Zimpfer, Air Division
US Environmental Protection Agency
75 Hawthorne Street
San Francisco, CA 94105-3901
415-947-8715
zimpfer.amy@epa.gov

----- Forwarded by Amy Zimpfer/R9/USEPA/US on 09/16/2005 01:46 PM -----

Marty Kay
<mkay@aqmd.gov>

09/16/2005 11:20 AM

To
Amy Zimpfer/R9/USEPA/US@EPA

cc

Subject
RE: BHP Billiton Cabrillo Port LNG Deepwater Port

I participate on Southern California Gas Company's gas quality techical committee, and have been involved with the FERC and CPUC proceedings on gas quality. I'm the lead staff person here. We've heard that BHP Billiton would be bringing in high quality gas, compared to the other LNG terminals.

Martin Kay
Program Supervisor
South Coast Air Quality Management District
21865 Copley Dr.
Diamond Bar, CA 91765-3252
909.396.3115
mkay@aqmd.gov

-----Original Message-----
From: Zimpfer.Amy@epamail.epa.gov [mailto:Zimpfer.Amy@epamail.epa.gov]
Sent: Friday, September 16, 2005 9:18 AM
To: Marty Kay; Zoueshtiagh.Nahid@epamail.epa.gov
Subject: RE: BHP Billiton Cabrillo Port LNG Deepwater Port

Nahid--please followup on Marty's request. thanks

Marty--fyi--Nahid Zoueshtiagh is our lead on this LNG project. What role do you plan at the AQMD?

Amy Zimpfer, Air Division
US Environmental Protection Agency
75 Hawthorne Street
San Francisco, CA 94105-3901
415-947-8715
zimpfer.amy@epa.gov

Marty Kay
<mkay@aqmd.gov>

09/15/2005 07:52 AM

To: Amy Zimpfer/R9/USEPA/US@EPA

cc

Subject: RE: BHP Billiton Cabrillo Port LNG Deepwater Port

Please add Chung Liu and myself to your outreach mailing list for the BHP Billition project, and any other LNG projects EPA is involved with.

Martin Kay
Program Supervisor
South Coast Air Quality Management District
21865 Copley Dr.
Diamond Bar, CA 91765-3252
909.396.3115
mkay@aqmd.gov

-----Original Message-----
From: Chung Liu
Sent: Wednesday, September 07, 2005 1:17 AM
To: Marty Kay
Subject: FW: BHP Billiton Cabrillo Port LNG Deepwater Port

Marty,

Please call Dean Simmeroth of ARB that you and I would like to be in the coming meeting.

-----Original Message-----
From: Mohsen Nazemi
Sent: Tue 9/6/2005 6:26 PM
To: 'Zimpfer.Amy@epamail.epa.gov'
Cc: Rios.Gerardo@epamail.epa.gov; Zoueshtiagh.Nahid@epamail.epa.gov; Yannayon.Laura@epamail.epa.gov; dsimerot@arb.ca.gov; mtollstrup@arb.ca.gov; gyee@arb.ca.gov; mike@vcapcd.org; dresslert@sbcapcd.org; 'CantleP@sbcapcd.org'; Carol Coy; Chung Liu; Barry Wallerstein; Kurt Wiese; Peter Greenwald; Barbara Baird; Elaine Chang

Subject: BHP Billiton Cabrillo Port LNG Deepwater Port

Hi Amy. How are your? Thanks for the update on EPA's schedule on BHP Billiton's LNG Deep Water Port. I wanted to get back to you following our earlier discussions regarding this facility, as well as the SES Long Beach LNG Terminal.

> Nahid has offered to conference us in for the upcoming meeting that EPA has with the BHP Billiton project proponents. I appreciate the offer and would like to let EPA know that we are interested to participate via phone.
> Also you had previously asked me about how we plan to impose conditions on the SES permit to prevent "Hot Gas" from being delivered to the natural gas users here in South Coast, and after our last meeting here regarding BHP Billiton with CARB and other parties I had a phone call from Laura of your office also wanting to coordinate with us regarding this approach. I think the short answer to your question is that SES has been aware of our concern with the "Hot Gas" issue. As part of their LNG terminal in Long Beach, SES has proposed to install an LNG processing system which would not only convert liquid natural gas to gaseous natural gas, but it consists of systems (such as DeEthanizer and DeButanizer) that removes some of the higher heating value components from LNG. In their application, SES has indicated that the higher heating value (HHV) of their final product sold to the Gas Company or others would be in the range of 1,050 BTU/SCF. Presently our intentions are to impose this heating value limit as a requirement on their permit.
> Finally, at our last meeting here on BHP Billiton project with CARB and others we agreed to participate in a meeting/discussion with CARB and other agencies (such as CEC, VCAPCD, etc.) to also reach a better understanding on what should the characteristics (i.e. heating value) of the natural gas provided to the pipeline be, aside from the PUC standards, to prevent the distribution and burning of "Hot Gas" in the Southern California area. It was my understanding that CARB was going to take the lead in setting up this meeting/discussion.

Please let me know if you, Laura or Nahid have any other questions regarding LNG terminal. Thanks and hope to talk to you, or see you soon.

Mohsen Nazemi, P.E.
Assistant Deputy Executive Officer
Engineering and Compliance
South Coast Air Quality Management District
Tel.(909) 396-2662
Fax.(909)396-3895
mnazemi1@aqmd.gov

-----Original Message-----
From: Zimpfer.Amy@epamail.epa.gov
[mailto:Zimpfer.Amy@epamail.epa.gov]
Sent: Friday, September 02, 2005 6:50 PM
To: dmaul@energy.state.ca.us; MPrescott@comdt.uscg.mil; mike@vcapcd.org; mtollstrup@arb.ca.gov; gyee@arb.ca.gov; adettmer@coastal.ca.gov; Francis.Mardula@MARAD.DOT.GOV; Mohsen Nazemi; dresslert@sbcapcd.org; dsimerot@arb.ca.gov; OGGINSC@slc.ca.gov
Cc: Rios.Gerardo@epamail.epa.gov; Cort.Paul@epamail.epa.gov; Schmidt.Davidp@epamail.epa.gov;

Wesling.Mary@epamail.epa.gov;
Zoueshtiagh.Nahid@epamail.epa.gov;
Zemsky.Al@epamail.epa.gov; Yannayon.Laura@epamail.epa.gov;
Alkon.Margaret@epamail.epa.gov;
aquitania.manny@epamail.epa.gov;
aquitania.manny@epamail.epa.gov
Subject: BHP Billiton Cabrillo Port LNG Deepwater Port--Update on Public Outreach

Dear Colleagues:

On August 9th, I sent an email summarizing our public outreach plans for the Clean Air Act permit for the BHP Billiton Cabrillo Port Liquefied Natural Gas (LNG) Deepwater Port and I invited your participation. Thank you for those who provided me with names of people we will work with during our public outreach. I would like to update you on our latest thinking on EPA's public outreach effort for the air permitting portion of the proposed BHP LNG Facility. Recently, we learned theCalifornia State Lands Commission(SLC) plans to conduct an additional public process for the Revised Draft Environmental Impact Report including a review period and an additional public meeting. They have informed us their projected date for releasing the revised document is early December with a public workshop possibly in January. As a result, we have decided to harmonize our permit public outreach to coincide with SLC's. Wereleasing the revised document We plan to be available for the public hearing on the Revised Environmental Impact Report to be conducted by the SLC. Originally, as conveyed in my August 9th invitation, EPA was planning on conducting a stand-alone Open House in the mid-October 2005 timeframe. We have changed our plans to better harmonize our activities with the NEPA/CEQA process and to benefit from the concentration of interested public participants, government agencies and industry already gathered for the same purpose.

Specifically, we currently plan to attend the SLC public workshop to provide specific information on the air permitting process and the Cabrillo Deep Water Port air permit application. Our water colleagues may also join us to provide information on EPA's proposed wastewater discharge permit. Shortly after SLC's event, we plan to propose the draft air permit and begin the public comment period. We will hold a public hearing on the air permit sometime during the 60 day public comment period, perhaps in February 2006.

The primary purpose of EPA's outreach effort is to inform the public about the air permitting process, and provide general information on how they can get involved in providing comments. EPA is hopeful that our public outreach will be meaningful and productive and we will need your help and advice throughout the process. If you have any questions, please call me at (415)947-4146, or Manny Aquitania can be reached at (415)972-3977, or "aquitania.manny@epa.gov".

Thanks again.

Amy

Amy Zimpfer, Air Division
US Environmental Protection Agency
75 Hawthorne Street

San Francisco, CA 94105-3901
415-947-8715
zimpfer.amy@epa.gov